



US008907269B2

(12) **United States Patent**
Chalitsios et al.

(10) **Patent No.:** **US 8,907,269 B2**
(45) **Date of Patent:** **Dec. 9, 2014**

(54) **APPARATUS AND METHOD FOR PULSED NEUTRON GENERATION INCLUDING A HIGH VOLTAGE POWER SUPPLY**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 197 days.

(21) Appl. No.: **13/014,211**

(22) Filed: **Jan. 26, 2011**

(65) **Prior Publication Data**
US 2011/0186723 A1 Aug. 4, 2011

Related U.S. Application Data

(60) Provisional application No. 61/299,748, filed on Jan. 29, 2010.

(51) **Int. Cl.**
G01V 5/10 (2006.01)
G01V 5/04 (2006.01)
H05H 3/06 (2006.01)
G01N 23/09 (2006.01)

(52) **U.S. Cl.**
CPC **H05H 3/06** (2013.01); **G01N 2223/649** (2013.01); **G01N 23/09** (2013.01); **G01N 2223/204** (2013.01)
USPC **250/269.4**; **250/269.2**; **250/269.3**; **250/269.7**; **250/265**; **250/266**

(58) **Field of Classification Search**
USPC 250/269.4, 269.2, 269.3, 269.7, 265, 250/266
See application file for complete search history.

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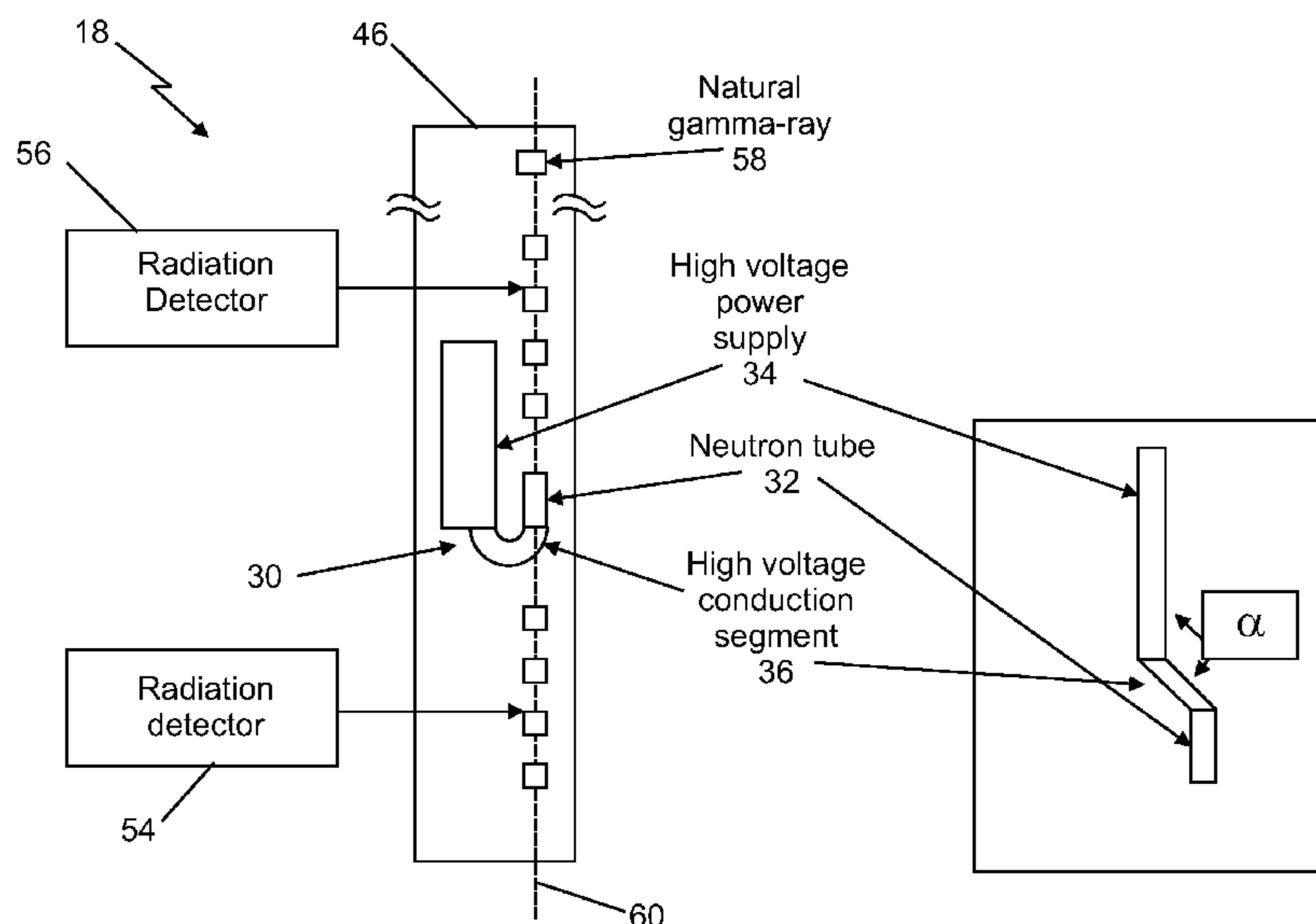
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(57) **ABSTRACT**

An apparatus for estimating at least one property of an earth formation is disclosed. The apparatus includes: a carrier configured to be disposed in the formation; a neutron tube disposed at the carrier and located on an axis; a high voltage power source disposed in the carrier and electrically connected to the neutron tube, the high voltage power source located remotely from the neutron tube; and at least one detector disposed in the carrier and located proximate to the neutron tube.

20 Claims, 7 Drawing Sheets



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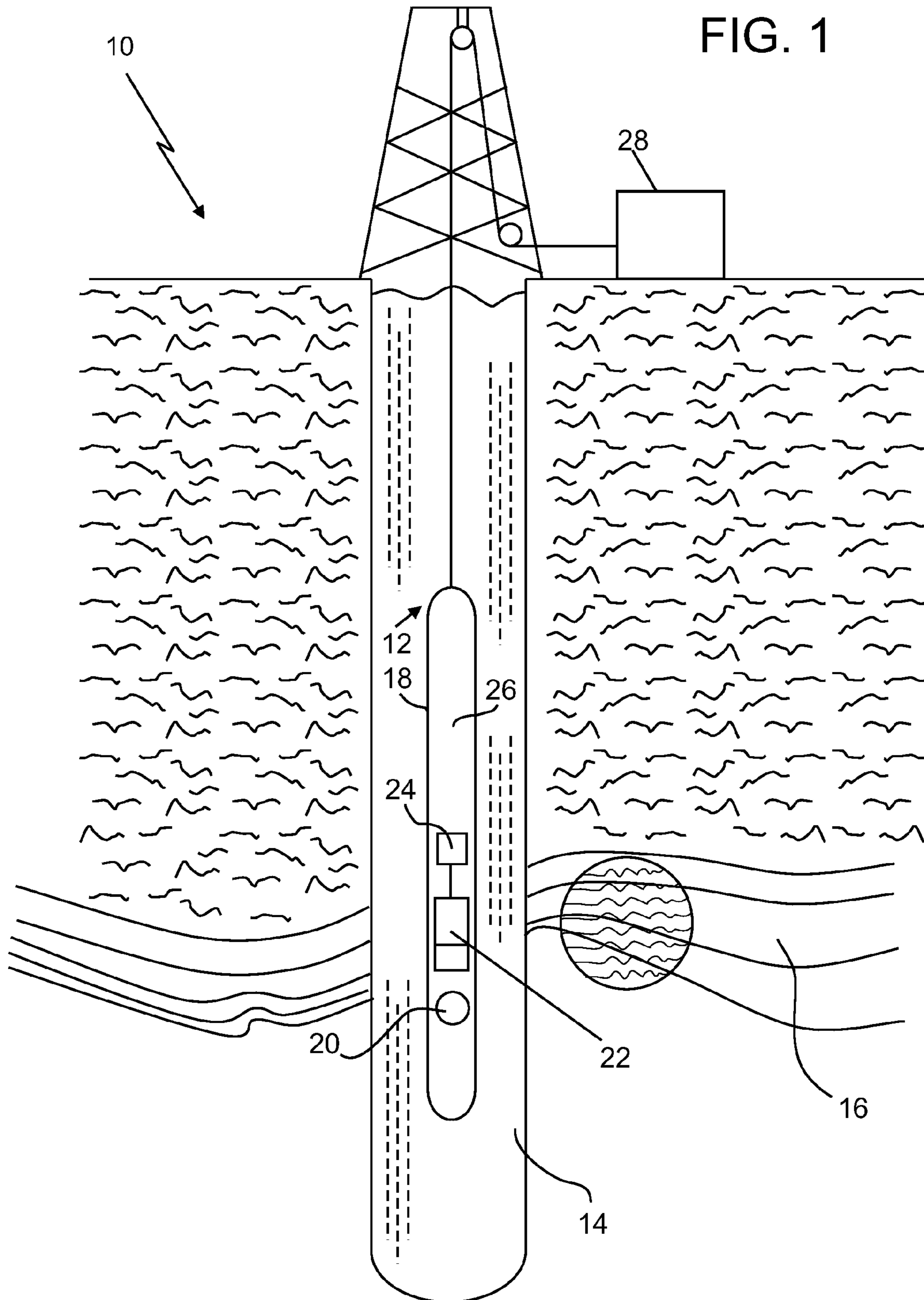
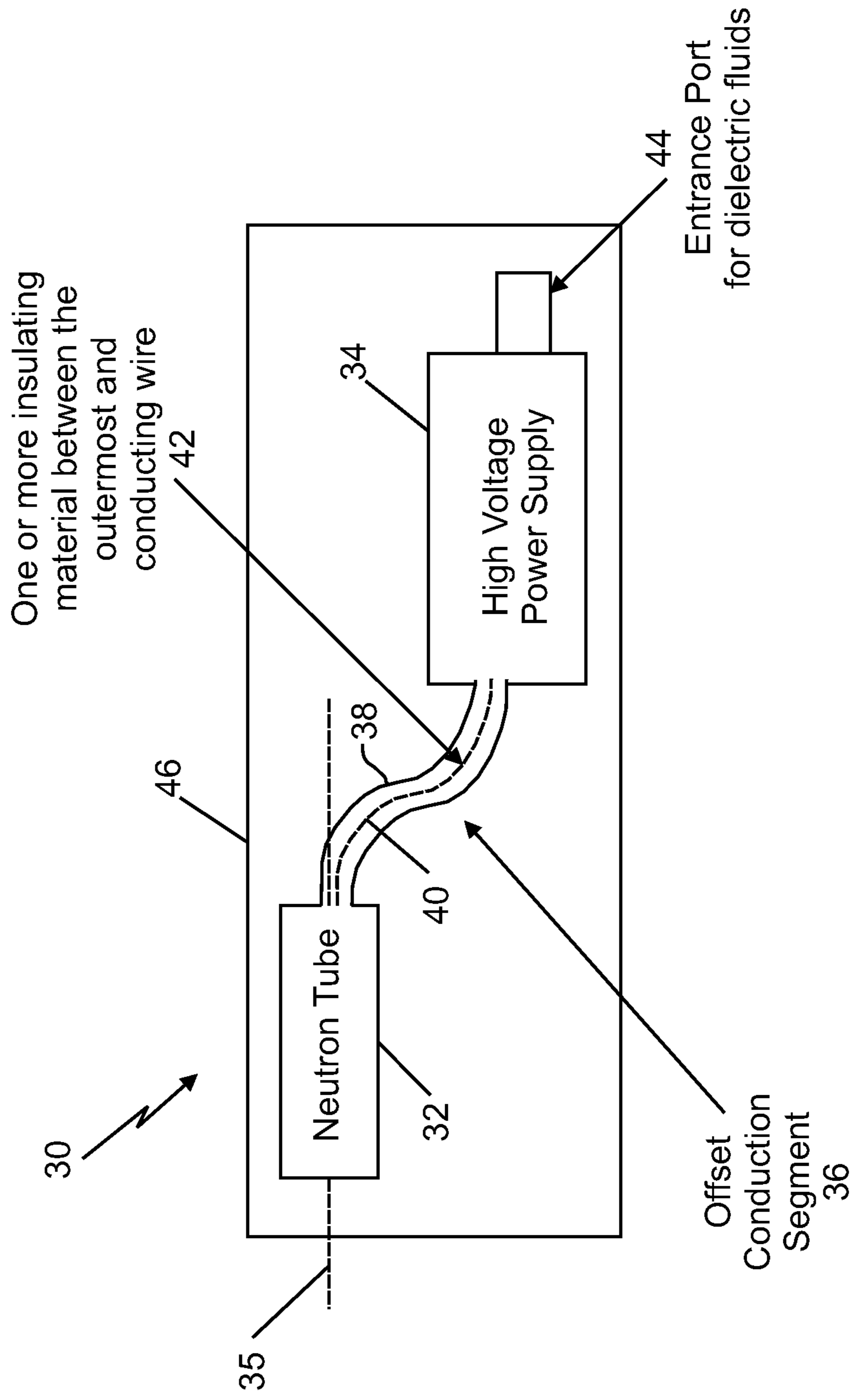


FIG. 2



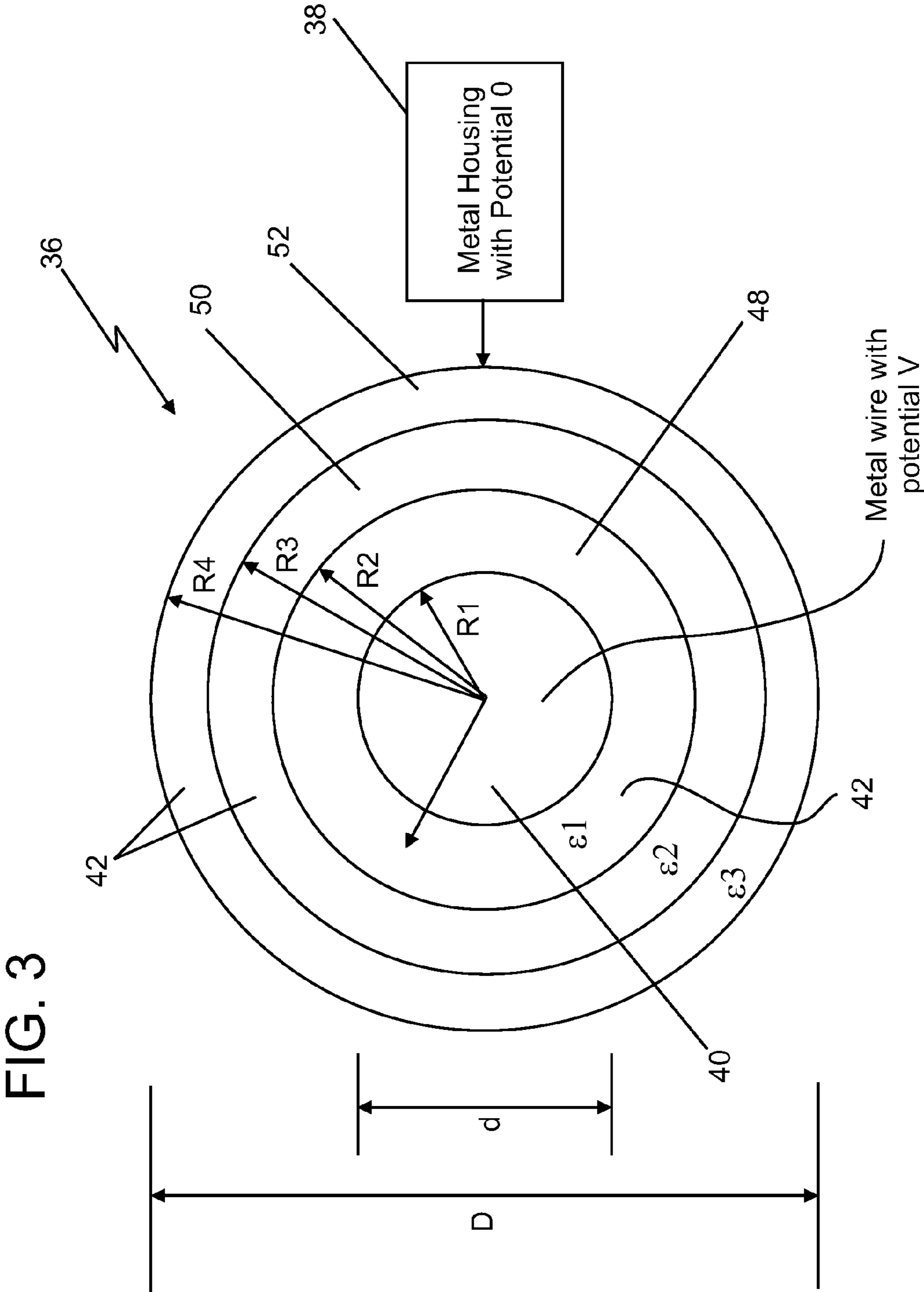
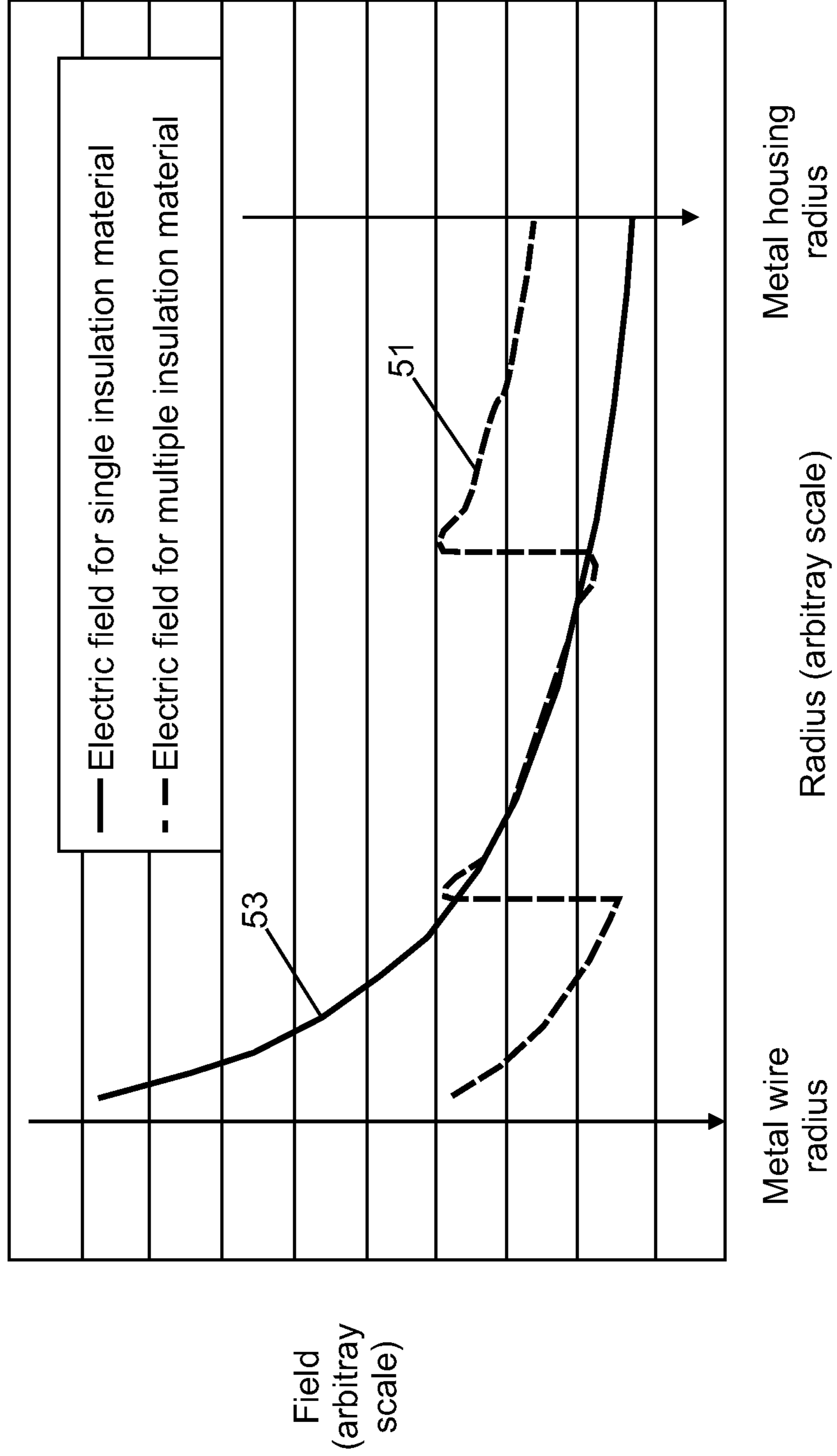
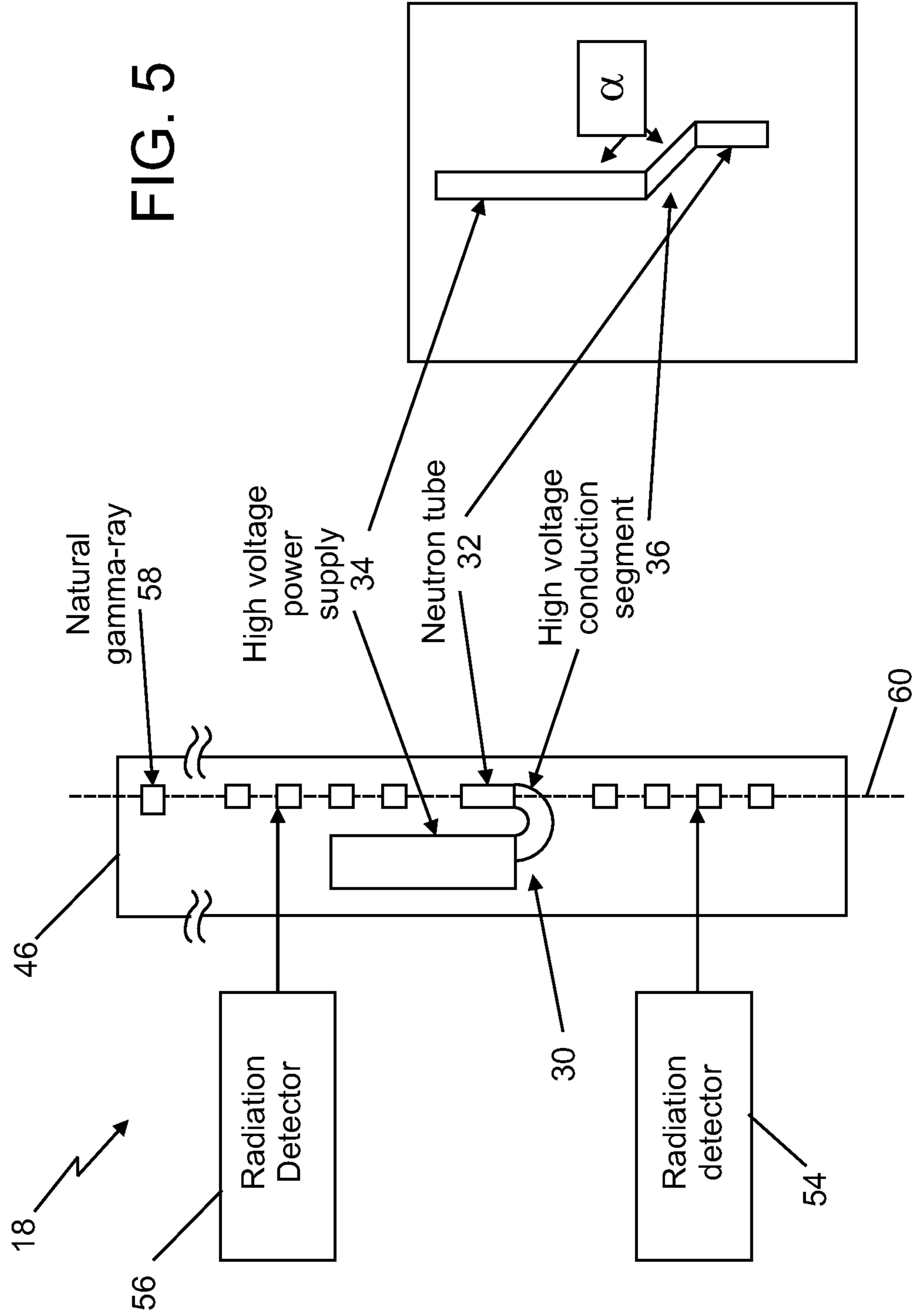


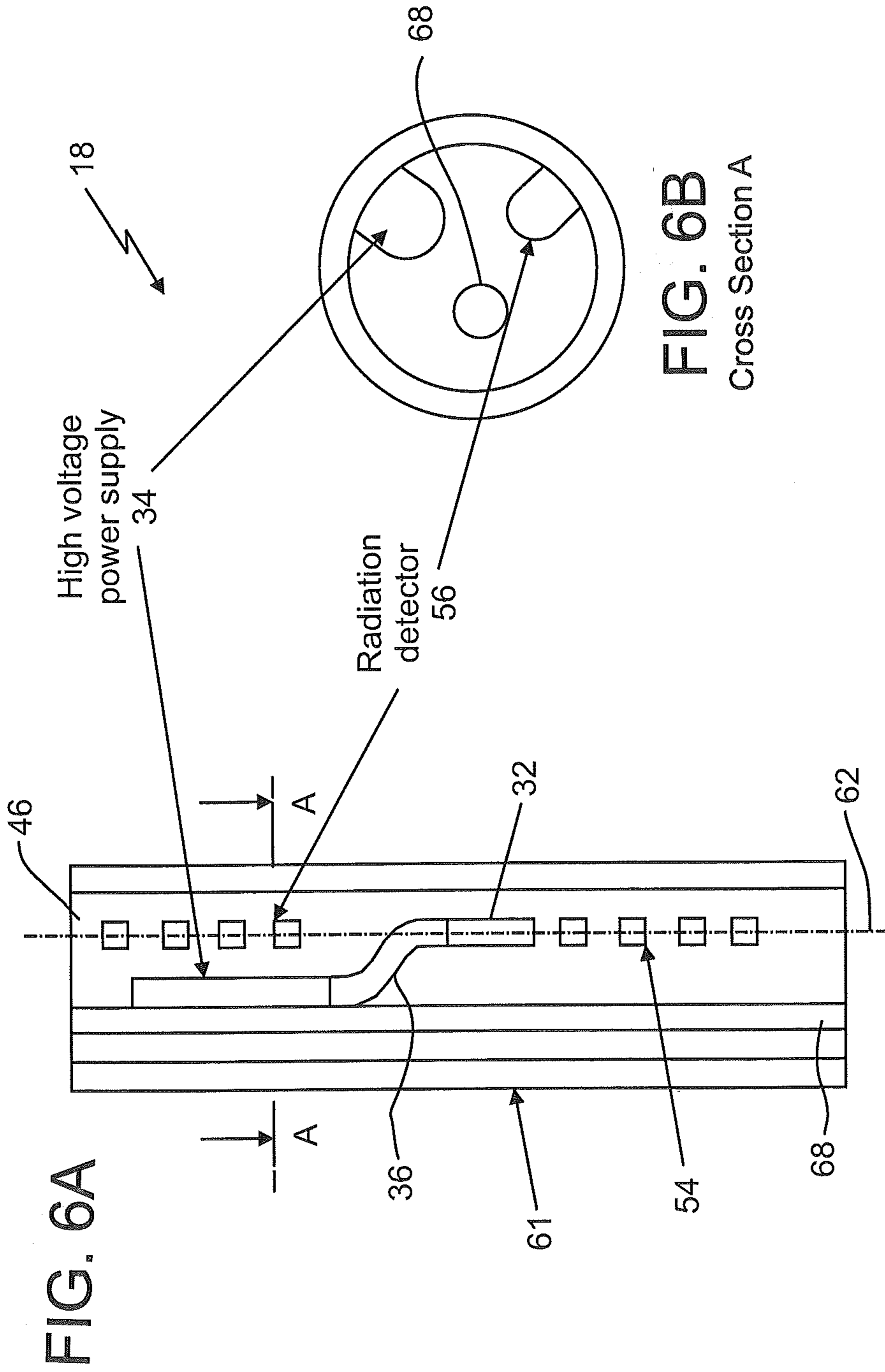
FIG. 3

FIG. 4

Field distribution within cylindrical metal housing







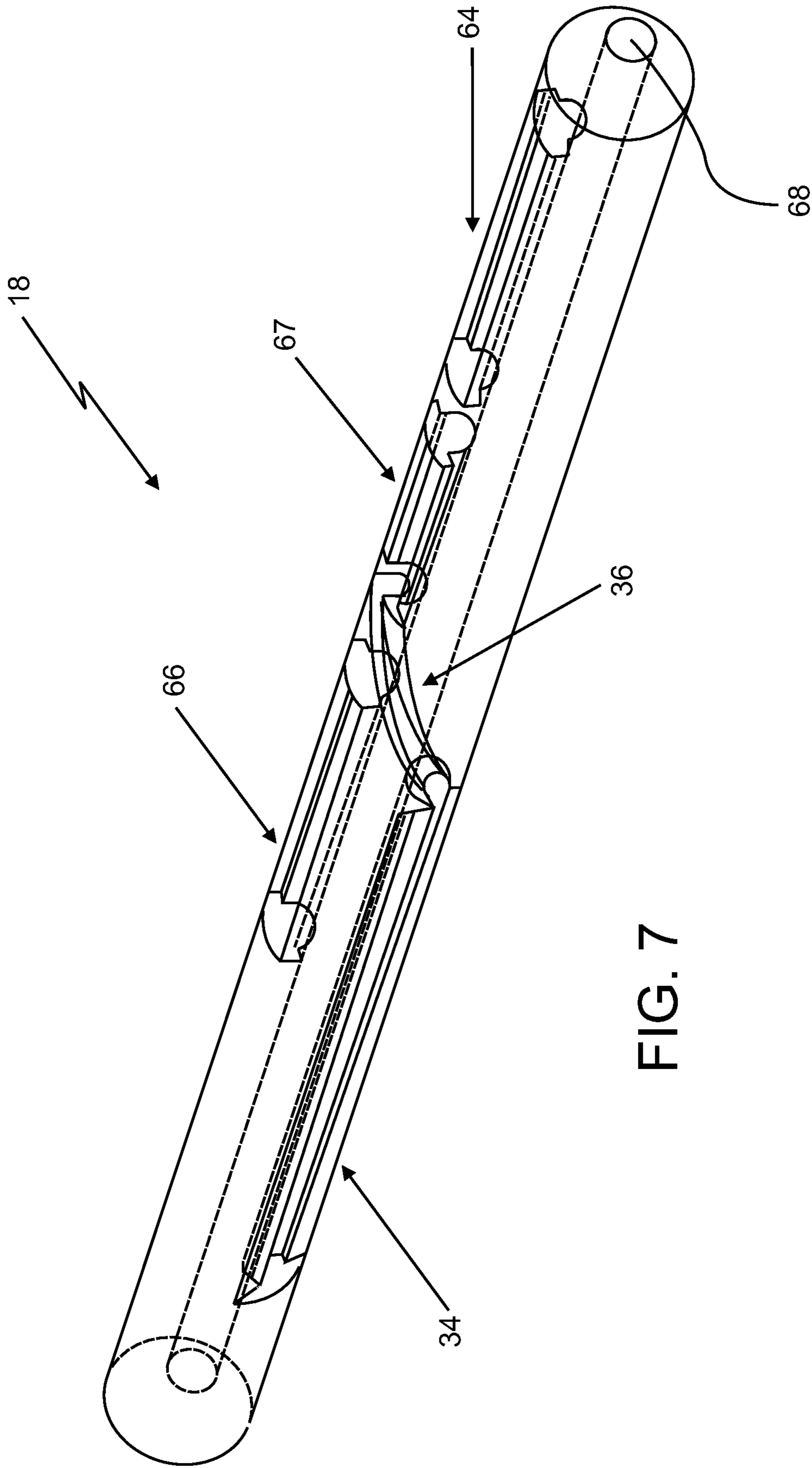


FIG. 7

1

APPARATUS AND METHOD FOR PULSED NEUTRON GENERATION INCLUDING A HIGH VOLTAGE POWER SUPPLY

CROSS REFERENCE TO RELATED APPLICATIONS

This application claims the benefit of an earlier filing date from U.S. Provisional Application Ser. No. 61/299,748 filed Jan. 29, 2010, the entire disclosure of which is incorporated herein by reference.

BACKGROUND

Pulsed neutron measurement tools are utilized in downhole environments for a variety of purposes, such as neutron based density and porosity measurements, and neutron induced gamma-ray spectral measurements.

Pulsed neutron generators for well logging applications normally consist of a sealed neutron tube, means of generating ions in a portion of the tube and means of extracting and accelerating the ions generated onto a target material. The acceleration of the ions is generally accomplished by way of a power supply capable of providing sufficient voltage to efficiently accomplish the desired reaction. The geometrical constraints associated with a neutron source housing such as a sonde or drill collar, together with the high voltage considerations imposed, are typically addressed by a linear coupling configuration between the high voltage power supply (HVPS) and the neutron generator tube. Such constraints often prevent emitters and detectors from being positioned in measurement devices at optimal locations.

SUMMARY

An apparatus for estimating at least one property of an earth formation includes: a carrier configured to be disposed in the formation; a neutron tube disposed at the carrier and located on an axis; a high voltage power source disposed in the carrier and electrically connected to the neutron tube, the high voltage power source located remotely from the neutron tube; and at least one detector disposed in the carrier and located proximate to the neutron tube.

An apparatus for estimating at least one property of an earth formation includes: an elongated tubular carrier configured to be disposed in the formation; a neutron tube disposed in the tubular carrier and located on an axis; at least one detector disposed in the carrier and located on the axis; and a high voltage power source disposed in the carrier and electrically connected to the neutron tube, the high voltage power source located remotely from the neutron tube.

A method of estimating at least one property of an earth formation includes: disposing a carrier in a borehole in the earth formation, the carrier including a neutron tube located on an axis and at least one detector located on the axis; supplying power to the neutron tube by activating a high voltage power source disposed in the carrier and electrically connected to the neutron tube, the high voltage power source located remotely from the neutron tube; emitting neutron pulses from the neutron tube into the formation; detecting at least one of neutrons and gamma rays emitted from the formation by the at least one detector; and estimating the at least one property based on at least one of the detected neutrons and the detected gamma rays.

BRIEF DESCRIPTION OF THE DRAWINGS

The subject matter which is regarded as the invention is particularly pointed out and distinctly claimed in the claims at

2

the conclusion of the specification. The foregoing and other features and advantages of the invention are apparent from the following detailed description taken in conjunction with the accompanying drawings in which:

5 FIG. 1 is a side cross-sectional view of an embodiment of a subterranean well drilling, evaluation, exploration and/or production system;

FIG. 2 is a side cross-sectional view of an embodiment of a tool including a neutron tube and a high voltage power source;

10 FIG. 3 is an axial cross-sectional view of an offset conduction segment of the tool of FIG. 2;

FIG. 4 is a graph showing an electrical field in the offset conduction segment of FIG. 3;

15 FIG. 5 is a side cross-sectional view of an embodiment of a downhole pulsed neutron measurement tool;

FIGS. 6A and 6B are a side cross-sectional view and an axial cross-sectional view, respectively, of an embodiment of a downhole pulsed neutron measurement tool; and

20 FIG. 7 is a perspective view of the pulsed neutron measurement tool of FIGS. 6A and 6B.

DETAILED DESCRIPTION

25 Apparatuses and methods for pulsed neutron measurements are described herein. The apparatuses and methods include a pulsed neutron generator including a high voltage power source for supplying accelerating voltage and current, which is configured to allow for effective placement of detectors used in pulsed neutron and other radiation measurements. In one embodiment, the pulsed neutron generator is configured to be disposed in a downhole environment, for example, in a wireline or logging-while-drilling (LWD) well logging application to facilitate measurements such as neutron based density, porosity measurements, and neutron induced gamma-ray spectral measurements. In one embodiment, the pulsed neutron generator includes a high voltage power source in an offset configuration to allow for enhanced measurement capabilities associated with allowing detectors to be more appropriately positioned with respect to a neutron emitting portion of the pulsed neutron generator.

In one embodiment, the tool includes a pulsed neutron source including a neutron tube and a remote high voltage power source, and one or more detectors such as radiation detectors. In one embodiment, the one or more detectors are located proximate to the neutron tube. For example, the neutron tube and the one or more detectors are placed in line with the neutron tube and/or placed adjacent to the neutron tube for optimal response to formation variables.

50 Referring to FIG. 1, an exemplary embodiment of a subterranean well drilling, evaluation, exploration and/or production system 10 includes a borehole string 12 that is shown disposed in a borehole 14 that penetrates at least one earth formation 16 during a subterranean operation. As described herein, "formations" refer to the various features and materials that may be encountered in a subsurface environment and surround the borehole. In one embodiment, the borehole 14 is a cased borehole or an open borehole. In one embodiment, the borehole string includes a downhole tool 18 such as a well logging tool. In this example, the downhole tool 18 is a wireline tool, but is not limited thereto. For example, the downhole tool 18 can be incorporated with a drill string for logging-while-drilling (LWD) applications, such as when the borehole 14 is not completed with a casing. The downhole tool 18 is not limited to the embodiments described herein, and may be disposed with any suitable carrier. A "carrier" as described herein means any device, device component, com-

combination of devices, media and/or member that may be used to convey, house, support or otherwise facilitate the use of another device, device component, combination of devices, media and/or member. Exemplary non-limiting carriers include drill strings of the coiled tube type, of the jointed pipe type and any combination or portion thereof. Other carrier examples include casing pipes, wirelines, wireline sondes, slickline sondes, drop shots, downhole subs, bottom-hole assemblies, and drill strings.

The downhole tool **18**, in one embodiment, is configured as a pulsed neutron spectroscopy tool. The tool **18** includes, for example, at least one pulsed neutron source **20** and at least one detector **22**. Examples of the at least one detector include radiation detectors such as gamma ray detectors and neutron detectors. In one embodiment, electronics **24** are also included for controlling the pulsed neutron source **20** and/or the at least one detector **22**, and/or for storing, transmitting and/or processing signals and/or data generated by the at least one detector **22**. The number of pulsed neutron sources **20** and detectors **22** is not limited. In one embodiment, the at least one gamma ray detector **22** is a scintillation detector that is configured to detect the presence of gamma rays and gamma ray energy levels. Scintillation detectors are generally capable of generating signals and/or data representative of both inelastic and capture gamma ray energy spectra.

The downhole tool **18** includes a housing **26** such as a sonde configured to house at least the neutron source **20** and the at least one detector **22**. In one embodiment, the housing also includes the electronics **24**. In one embodiment, the tool **18** is equipped with transmission equipment to communicate ultimately to a surface processing unit **28**. Such transmission equipment may take any desired form, and different transmission media and methods may be used. Examples of connections include wired, fiber optic, and wireless connections.

Referring to FIG. 2, an exemplary embodiment of the tool **18** includes a neutron source or neutron generator **30** that includes a neutron tube **32** electrically connected to a high voltage power supply (HVPS) **34**. In one embodiment, “high voltage” refers to a voltage of about 75 kilovolts (kV) or greater. In one embodiment, the HVPS **34** is configured to supply a voltage of at least about 90 kV. As described herein, a “neutron tube” refers to any device configured to accelerate ions and emit neutrons in response to the application of appropriate energy, such as by the HVPS **34**. The neutron tube **32** accordingly acts as a neutron emitter or source and may include various components for emitting neutrons, including ion sources, ion optic elements, and beam targets. The components are disposed in a housing, such as a vacuum tight enclosure. In one embodiment, the neutron tube **32** is a cylindrical tube, although any suitable shape or configuration may be used.

In one embodiment, the HVPS **34** is positioned remotely from the neutron tube **32** at a selected distance and location relative to the neutron tube **32** in a housing suitable for disposition in a downhole environment, such as a sonde or cartridge. The HVPS **34** may be the largest geometrical component of the neutron source **30**. The remote positioning of the HVPS **34**, or as alternately considered, the remote positioning of the neutron tube **32**, allows detectors to be positioned at locations that would not otherwise be allowed. In one embodiment, the HVPS **34** is at an offset position relative to the neutron tube **32**. For example, the neutron tube **32** is located on an axis **35**, and the HVPS **34** is offset from the axis **35**. The axis **35**, in one embodiment, is the major axis of the neutron tube **32**, although the axis **35** may intersect the neutron tube **32** at any desired location and have any desired

orientation. In one example, “offset” refers to a position at which the major axis or other location in the HVPS **34** does not intersect the axis **35**.

The HVPS **34**, in one embodiment, is electrically connected to the neutron tube **32** via at least one conductor **36** capable of transmitting high voltage electricity. In one embodiment, the conductor **36** is an offset conduction segment **36** that can be curved or bent, or otherwise configured to effect an electrical connection between the neutron tube **32** and the HVPS **34**. The offset conduction segment **36** can be bent to various shapes or directions. In one embodiment, the offset conduction segment **36** includes a support structure including, for example, one or more solid dielectric supports having selected voltage withstanding capability, and a ground plane to complete an electrical circuit between the neutron tube **32** and the HVPS **34**. The offset conduction segment **36** is, in one embodiment, a tubular and/or cylindrical structure, although any suitable shape may be employed. In one embodiment, the ground plane includes an exterior conductive housing **38** having a conductive wire **40** and one or more insulating materials **42** disposed therein. The insulating materials **42** include one or more solid dielectric materials. In one embodiment, the insulating materials **42** include one or more gaseous and/or liquid dielectric materials that may be disposed within the exterior housing **38** and/or introduced into the exterior housing **38** via, for example, an entrance port **44** located in the HVPS **34** or at another desired location.

In one embodiment, the neutron tube **32**, the HVPS **34** and the offset conduction segment **36** are installed in a housing **46**. The housing **46** may be made from any desired metallic or other material capable of withstanding downhole environments. Examples of such materials include materials chosen to reduce or minimize radiation production, such as titanium, stainless steel, and alloys including superalloys (e.g., Inconel™, Special Metals Corporation). The shape of the housing **46** may be cylindrical, but is not limited thereto. The shapes and sizes of the housing **46**, the neutron tube **32**, the HVPS **34** and the offset conduction segment **36** can have different shape and sizes.

Referring to FIG. 3, in one embodiment, the offset conduction segment **36** includes a metal conductor such as the wire **40** and various insulating materials **42** for support of the wire **40** and/or control of electric stresses around the wire **40**. The wire **40**, for example, is a metal wire with a diameter optimized to reduce electric stress on the supporting insulation materials **42**.

The wire **40** has a first diameter “d” and the conductive housing **38** has a greater second diameter “D”. The ratio of d to D may be selected or optimized based on the dielectric properties of the insulating materials **42**, which in some embodiments are configured as structural support members of the offset conduction segment **36**. In one embodiment, the insulating materials **42** include multiple dielectric materials **48**, **50** and **52** each having differing permittivities “ ϵ ”. The dielectric materials **48**, **50** and **52** may be chosen to provide mechanical support and/or for the control of electric gradients or stresses such that catastrophic high voltage breakdown can be eliminated or reduced.

In the example shown in FIG. 3, the conduction segment **36** includes three layers of dielectric materials. Although this embodiment includes three cylindrical layers, the number and shape of such layers are not limited thereto. For example, the dielectric layers may be any combination of solid, liquid and/or gaseous layers. Having one or more solid layers may provide sufficient mechanical support to allow one or more gaseous and/or liquid dielectric layers to be included.

In one embodiment, the dielectric layers **48**, **50** and **52** are arranged to control electric stresses, for example, by making the electric field from the high potential wire **40** to the grounded exterior housing **38** more uniform than an electric field resulting from a single dielectric material.

In the example shown in FIG. **3**, an inner dielectric layer **48** surrounds the wire **40** (having a radius “R1” and an applied potential “V”) and has a permittivity “ ϵ_1 ” and an outer diameter “R2”, an intermediate dielectric **50** surrounds the inner layer **48** and has a permittivity “ ϵ_2 ” and an outer diameter “R3”, and an outer dielectric layer **52** surrounds the intermediate layer **50** and has a permittivity “ ϵ_3 ” and an outer diameter “R4”. The exterior housing **38** is grounded, surrounds the outer layer **52** and has an inner diameter incrementally greater than “R4”. The diameter of each layer may be chosen based on the permittivity of the layer material. For example, for a material with a given dielectric constant or permittivity, the thickness or diameter is selected to keep the maximum magnitude of fields in the layer below the dielectric strength of the material for given temperatures, such as for elevated temperatures. Such elevated temperatures include, for example, the temperatures typically present in downhole environments. In another example, the diameter and/or permittivity of each layer is selected so that the electric field is approximately proportional to $1/x$ at the interface of two different layers, where “x” is a radial distance from the central axis of the wire **40**.

FIG. **4** illustrates an example of the electric field E at various radial distances from the wire **40**. The resultant electric field **51** has a maximum in each layer, which is much less than the maximum of an electric field **53** produced in a single layer of insulating or dielectric material. This design thus restricts the maximum field in each insulating material **42** to a level below the material’s dielectric strength, and reduces the probability of electric break down in any single insulation layer such as dielectric layer **48**, **50** or **52**.

Referring to FIG. **5**, an exemplary embodiment of the tool **18** includes a pulsed neutron source or generator **20**, **30** and one or more detectors **22**. This configuration provides a compact and integrated apparatus for measuring the characteristics of earth formations surrounding a borehole, including thermal or epithermal neutron porosity, sigma, mineralogy, carbon-oxygen ratio, which can be used, for example, as an indication of formation fluid and sourceless density. In one embodiment, the tool **18** is configured as a wireline tool, such as in the system of FIG. **1**.

In one embodiment, the detectors **22** are configured as radiation detectors. Such radiation detectors are configured to detect various types of radiation and/or radiation particles such as neutrons, alpha particles, beta particles, x-rays, electrons, protons, gamma rays and others. Examples of radiation detectors include neutron detectors, proton, electron, alpha and beta particle detectors, x-ray and gamma ray detectors, and others. Those skilled in the art will recognize that radiation particles and radiation detectors can take many forms.

The neutron generator **30** includes the neutron tube **32** and the offset HVPS **34** connected to the neutron tube **32** via the offset conduction segment **36**. The detectors **22** include various detectors such as radiation detectors **54**, **56**. For example, radiation detectors **54** may include one or more scintillation gamma ray detectors **54** and radiation detectors **56** may include one or more neutron detectors **56**. In one embodiment, one or more additional radiation detectors **58** are included to detect natural background radiation particles emitted from the formation. The additional detectors **58** can be positioned sufficiently far removed and/or shielded from the neutron generator **30**. For example, the additional detec-

tors are placed along the leading and/or trailing sides of the tool **18**. The additional detectors **58** allow for measuring natural formation radioactive constituents such as K—U—Th along the leading end of the housing **46** and/or activation products along the trailing end. “Leading” and “trailing” ends are defined relative to the location of the neutron tube **32**. For example, the leading end is the end of the tool **18** that passes a reference location prior to the neutron tube **32** when the tool **18** is moved during a measurement operation.

The HVPS **34** is located in an offset position relative to the neutron tube **32** so that the detectors **22** can be positioned proximate to the neutron tube **32**. This design allows radiation detectors **54**, **56** to be placed optimally with respect to the neutron source **32**. In one embodiment, a “proximate” location refers to a location that would be unavailable if the HVPS **34** were to be located in line with the neutron tube **32**. Examples of such proximate locations include locations adjacent to and/or in the immediate vicinity of the neutron tube **32**.

Other proximate locations include locations linearly co-located along an axis with the neutron tube **32**. For example, one or more of the radiation detectors **54**, **56** are linearly co-located with the neutron tube **32**, i.e., placed in line with the neutron tube **32** at the same side in the tool **18**. FIG. **5** shows the neutron tube **32** and the radiation detectors **54**, **56** located on an axis **60**. The axis **60** is, for example, a major axis of the neutron tube **32**.

In one embodiment, the radiation detectors **56** are located on the trailing side of the neutron tube **32** since they are insensitive to formation activation gamma rays. If both thermal and epithermal detectors **56** are included, they are small enough that they may be placed side-by-side in the pockets. The positions and sizes of all the radiation detectors **54**, **56** can be adjusted for optimized measurement results, and the position of neutron tube **32** can also be adjusted for better measurements.

FIGS. **6A**, **6B** and **7** show an exemplary embodiment of the tool **18**. FIGS. **6A** and **6B** are side and axial cross-sectional views, respectively, of the tool **18**, and FIG. **7** is a perspective view of the tool **18**. In one embodiment, the tool **18** is configured as a LWD tool, and the housing **46** includes one or more sleeves **61** to protect the neutron generator **30** and the radiation detectors **54**, **56**. The tool **18**, in this embodiment, includes the neutron generator **30** including the neutron tube **32**, the offset conductive segment **36** and the HVPS **34**. As illustrated, the conduction segment **36** is smoothly curved between the neutron tube **32** and the HVPS **34**, although the conduction segment may follow any desired path between the neutron tube **32** and the HVPS **34**. One or more radiation detectors **54**, **56** are co-located on an axis **62** with the neutron tube **32**. For example, radiation detectors **54** may include one or more gamma ray detectors **54** and radiation detectors **56** may include one or more neutron detectors **56**.

In one embodiment, the neutron tube **32**, the HVPS **34** and/or the radiation detectors **54**, **56** are disposed in respective protective housings or chambers. The housings or chambers may be made from materials such as metals sufficient to protect the components from downhole environments or to insulate components. In one example, the radiation detectors **54** are disposed in a corresponding radiation detector chamber **64**, the radiation detectors **56** are disposed in a corresponding radiation chamber **66** and the neutron tube **32** is disposed in a neutron tube chamber **67**. In FIG. **7**, only two chambers for radiation detectors are included, however, there could be any number of chambers for radiation detectors.

In one embodiment, an interior conduit such as a mud channel **68** is disposed in the tool **18**, and is configured to

connect in fluid communication with the borehole and/or other components of the system **10**, such as mud channels in neighboring LWD collars. The mud channel **68** may take any desired path through the tool **18**, for example to allow for desired positioning of the radiation detectors **54**, **56**. For example, a deviated mud channel **68** might be used to allow for other complimentary positioning of detectors to accomplish specific enhancements. In one embodiment, the HVPS **34**, the mud channel **68**, and the radiation detectors **54**, **56** are placed in the same longitudinal region in the housing **46**, so that all the components may be distributed uniformly in the housing **46**, as shown in FIG. **6B**. In one embodiment, the HVPS **34**, the neutron tube **32** and/or the detectors **54**, **56**, **58** are disposed on an interior surface of the housing **46** or an exterior surface of the mud channel **68**.

The tool **18** may incorporate a variety of other features and sensors beyond that described in the above embodiments. For example, radiation shielding made from Boron or other suitable materials may be applied inside the housing **46** and/or around selected detectors to eliminate neutron activation of the tool itself. In addition, the tool **18** may include or otherwise be utilized in conjunction with any number of additional measurement tools such as nuclear magnetic resonance (NMR) tools, nuclear quadrupole resonance (NQR) tools, resistivity tools, seismic tools, porosity sensors and others.

The above described systems and/or apparatuses may be employed in a method of estimating at least one property of an earth formation. The method may be performed in conjunction with the system **10** and/or the downhole tool **18**, but is not limited thereto.

In a first stage of the method, the pulsed neutron tool **18** is disposed in the borehole **14**, and one or more measurements are taken. Measurements are taken by activating the neutron source **20**, **30** and detecting resultant gamma ray photons and/or neutrons via the detectors **22**, **54**, **56** and/or **58**. In one embodiment, one or more measurements are taken for each of a plurality of borehole depths. Measurements may include measurements of both capture and inelastic interactions.

Measurements may be taken by supplying power to the pulsed neutron source by activating the HVPS **34** connected to the pulsed neutron tube **32**, emitting neutrons from the pulsed neutron tube **32** into the formation, and detecting at least one of neutrons and gamma rays emitted from the formation by the at least one detector.

In one embodiment, the signals generated by the detectors **22**, **54**, **56** and/or **58** are received and/or processed by the electronics **24** and/or the surface processing unit **28**. The signals can be analyzed to determine inelastic and capture measurements, and energy and/or time spectra for the measurements can be calculated.

In one embodiment, the taking of measurements from the tool **18** is recorded in relation to the depth and/or position of the tool **18**, which is referred to as "logging", and a record of such measurements is referred to as a "log". Examples of logging processes that can be performed by the system **10** and in conjunction with the methods described herein include measurement-while-drilling (MWD) and logging-while-drilling (LWD) processes. Additional examples of logging processes include logging measurements after drilling, wireline logging, pipe-conveyed logging operations and drop shot logging. The data retrieved during these processes may be transmitted to the surface, and may also be stored with the tool **18** for later retrieval.

In a second stage **42**, various properties of the formation are estimated. Examples of such properties include porosity, saturation, sigma values, mineralogy and a carbon-oxygen ratio.

The apparatuses and methods described herein have various advantages over prior art apparatuses and techniques. The apparatuses and methods allow for placement of detectors in locations proximate to the neutron tube that would otherwise be unavailable in prior art configurations. Prior art configurations generally use a neutron source that includes a HVPS connected adjacent to the neutron tube via a HV coupling unit. A typical prior art source includes a neutron tube and a HVPS packaged together in the same metal cylindrical tube. The apparatuses and methods described herein feature the HVPS connected remotely and/or in an offset position relative to the neutron tube, which allows detectors to be positioned in locations proximate and/or adjacent to the neutron tube that are unavailable in such prior art tools. In addition, the remotely located HVPS may provide more space for scintillation detectors especially in a tool with small radius.

In connection with the teachings herein, various analyses and/or analytical components may be used, including digital and/or analog systems. The system may have components such as a processor, storage media, memory, input, output, communications link (wired, wireless, pulsed mud, optical or other), user interfaces, software programs, signal processors (digital or analog) and other such components (such as resistors, capacitors, inductors and others) to provide for operation and analyses of the apparatus and methods disclosed herein in any of several manners well-appreciated in the art. It is considered that these teachings may be, but need not be, implemented in conjunction with a set of computer executable instructions stored on a computer readable medium, including memory (ROMs, RAMs), optical (CD-ROMs), or magnetic (disks, hard drives), or any other type that when executed causes a computer to implement the method of the present invention. These instructions may provide for equipment operation, control, data collection and analysis and other functions deemed relevant by a system designer, owner, user or other such personnel, in addition to the functions described in this disclosure.

One skilled in the art will recognize that the various components or technologies may provide certain necessary or beneficial functionality or features. Accordingly, these functions and features as may be needed in support of the appended claims and variations thereof, are recognized as being inherently included as a part of the teachings herein and a part of the invention disclosed.

While the invention has been described with reference to exemplary embodiments, it will be understood by those skilled in the art that various changes may be made and equivalents may be substituted for elements thereof without departing from the scope of the invention. In addition, many modifications will be appreciated by those skilled in the art to adapt a particular instrument, situation or material to the teachings of the invention without departing from the essential scope thereof. Therefore, it is intended that the invention not be limited to the particular embodiment disclosed as the best mode contemplated for carrying out this invention.

The invention claimed is:

1. An apparatus for estimating at least one property of an earth formation, comprising:
 - a carrier configured to be disposed in the formation;
 - a neutron tube disposed at the carrier and extending longitudinally along the carrier, the neutron tube including at least one neutron source enclosed in a sealed housing;
 - a high voltage power source disposed in the carrier and electrically connected to the neutron tube, the high voltage power source located remotely from the neutron tube and offset from the neutron tube such that the high

voltage power source does not intersect any longitudinal axis of the sealed housing; and

at least a first detector and a second detector disposed in the carrier and located proximate to the neutron tube, the first detector located above the neutron tube, and the second detector located below the neutron tube.

2. The apparatus of claim 1, wherein the first detector is located on a longitudinal axis of the neutron tube and above the neutron tube, and the second detector is located on the longitudinal axis and below the neutron tube.

3. The apparatus of claim 1, further comprising a conduction segment configured to electrically connect the high voltage power supply to the neutron tube, the conduction segment including a high voltage conductor, at least one insulating material surrounding the conductor, and a grounded conductive housing surrounding the insulating material.

4. The apparatus of claim 1, wherein the first detector is located adjacent to the neutron tube and above the neutron tube, and the second detector is located adjacent to the neutron tube and below the neutron tube.

5. The apparatus of claim 1, wherein the first detector and the second detector are longitudinally co-located with the high voltage power source.

6. The apparatus of claim 1, wherein the carrier includes a hollow tubular member, and the neutron tube, the first detector, the second detector and the high voltage power source are disposed on an interior surface of the hollow tubular member.

7. The apparatus of claim 1, wherein the neutron tube includes at least one particle accelerator enclosed within the sealed housing and connected to the neutron source.

8. The apparatus of claim 7, wherein the neutron source is an ion source and the at least one particle accelerator includes an ion accelerator, the ion source and the ion accelerator enclosed within the sealed housing.

9. The apparatus of claim 1, wherein the carrier includes an interior conduit, and the neutron tube, the first detector, the second detector and the high voltage power source are disposed on an exterior surface of the conduit.

10. The apparatus of claim 1, wherein the neutron tube is located on a longitudinal axis between the first detector and the second detector, and at least one of the first detector and the second detector is longitudinally co-located with the high voltage power supply.

11. An apparatus for estimating at least one property of an earth formation, comprising:

an elongated tubular carrier configured to be disposed in the formation;

a neutron tube disposed in the tubular carrier and extending longitudinally along the carrier, the neutron tube including at least one neutron source enclosed in a sealed housing;

at least a first detector and a second detector disposed in the carrier and located on a longitudinal axis of the neutron tube, the first detector located above the neutron tube, and the second detector located below the neutron tube; and

a high voltage power source disposed in the carrier and electrically connected to the neutron tube, the high voltage power source located remotely from the neutron

tube and offset from the neutron tube such that the high voltage power source does not intersect any longitudinal axis of the sealed housing.

12. The apparatus of claim 11, wherein the first detector is located on a longitudinal axis of the neutron tube and above the neutron tube, and the second detector is located on the longitudinal axis and below the neutron tube.

13. The apparatus of claim 11, wherein the tubular carrier includes a hollow tubular member and the neutron tube, the first detector, the second detector and the high voltage power source are disposed on an interior surface of the hollow tubular member.

14. The apparatus of claim 11, wherein the first detector and the second detector are longitudinally co-located with the high voltage power source.

15. The apparatus of claim 11, wherein the elongated tubular carrier includes a protective housing surrounding the hollow tubular member, the neutron tube, the first detector, the second detector and the high voltage power source.

16. The apparatus of claim 11, wherein the neutron tube is located on a longitudinal axis between the first detector and the second detector, and at least one of the first detector and the second detector is longitudinally co-located with the high voltage power supply.

17. A method of estimating at least one property of an earth formation, comprising:

disposing a carrier in a borehole in the earth formation, the carrier including a neutron tube extending longitudinally along the carrier and at least a first detector and a second detector located on a longitudinal axis of the neutron tube, the first detector located above the neutron tube and the second detector located below the neutron tube, the neutron tube including at least one neutron source enclosed in a sealed housing;

supplying power to the neutron tube by activating a high voltage power source disposed in the carrier and electrically connected to the neutron tube, the high voltage power source located remotely from the neutron tube and offset from the neutron tube such that the high voltage power source does not intersect any longitudinal axis of the sealed housing;

emitting neutron pulses from the neutron tube into the formation;

detecting at least one of neutrons and gamma rays emitted from the formation by at least one of the first detector and the second detector; and

estimating the at least one property based on at least one of the detected neutrons and the detected gamma rays.

18. The method of claim 17, wherein the first detector and the second detector include at least one of: a neutron detector and a gamma ray detector.

19. The method of claim 17, wherein the first detector and the second detector are longitudinally co-located with the high voltage power source.

20. The method of claim 17, wherein the at least one property includes at least one of porosity, saturation, sigma, sourceless density, minerology and a carbon-oxygen ratio.